Comprehensive Evaluation and Strategies for Sustainable Management of Agricultural Production Units

Evaluación Integral y Estrategias para el Manejo Sostenible de las Unidades de Producción Agropecuaria

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Enohemit Olivero-Vega
Universidad Simón Bolívar. Barranquilla, (Colombia)
enohemit.olivero@unisimon.edu.co

Ana Torregrosa-Espinosa
Universidad de la Costa CUC. Barranquilla, (Colombia)
atorregr4@cuc.edu.co

María Auxiliadora, Iglesias-Navas
Universidad Simón Bolívar. Barranquilla, (Colombia)
maria.iglesias@unisimon.edu.co

Alejandra Quintero-Linero
Universidad Popular del Cesar. Valledupar, (Colombia)
alejandraquinterol@unicesar.edu.co

David Blanco-Alvarez
Universidad de la Costa CUC. Barranquilla, (Colombia)
dblanco6@cuc.edu.co

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Abstract

Background and objectives: This article analyzes the comprehensive assessment and enhancement of the sustainable management of Agricultural Production Units (APUs) in the departments of Atlántico, César, and Magdalena in the Caribbean region of Colombia. The main objective is to identify challenges and opportunities for enhancing agricultural sustainability and propose appropriate strategies within a local context. Methods: The research employed a mixed methodological approach, incorporating APU diagnosis; strengths, weaknesses, opportunities, and threats analysis; and structured surveys administered to agricultural producers in each department. Moreover, secondary sources were employed to assess sustainable agricultural practices and key environmental variables. Findings: APUs in the Caribbean region face significant challenges, including limited access to technology, inefficient soil management, and scarce water resources. In Atlántico, 40% of producers lack education in soil studies. In Cesar, 30% of soils are degraded. In Magdalena, 70% are affected by salinization. These results emphasize the need to adopt agroecological technologies and strategies adjusted to the local context to ensure agricultural sustainability and resilience. Conclusion: This study highlights the urgency of implementing comprehensive strategies that consider regional specific characteristics. Designing public policies based on local diagnoses, technical training, and effective knowledge conveyance are essential to ensure sustainable agricultural development. These actions strengthen food safety and support the achievement of the Sustainable Development Goals, thereby positioning the agricultural sector as a key driver for regional development

Keywords
Sustainable Agriculture, Agroecology, Resource Optimization, Climate Resilience, Food Security

Resumen

Introducción: Las Unidades de Producción Agropecuaria (UPA) de Atlántico, Cesar y Magdalena sostienen la seguridad alimentaria regional, pero afrontan desequilibrios edáficos, hídricos y tecnológicos que comprometen su sostenibilidad.
Objetivo: Identificar los retos y oportunidades para mejorar la sostenibilidad agrícola de las UPA y proponer estrategias ajustadas al contexto local.
Metodología: Se aplicó un enfoque mixto que combinó diagnóstico participativo de UPA, encuestas estructuradas a productores (n = X), análisis FODA y revisión de fuentes secundarias sobre prácticas agroecológicas y variables ambientales clave.
Resultados: La adopción tecnológica es limitada (≤ 40 %); en Atlántico, el 40 % de los productores carece de formación en estudios de suelos; en Cesar, el 30 % de los suelos está degradado; y en Magdalena, el 70 % de las UPA presenta salinización. Las deficiencias en manejo hídrico y conservación del suelo reducen la resiliencia productiva.
Conclusiones: Urge impulsar políticas públicas basadas en diagnósticos locales que incluyan capacitación técnica, difusión de tecnologías agroecológicas y gestión integrada de agua y suelo. Estas acciones fortalecerán la seguridad alimentaria y contribuirán al logro de los Objetivos de Desarrollo Sostenible, posicionando al sector agrícola caribeño como motor de desarrollo regional

Palabras clave
Agricultura sostenible, agroecología, optimización de recursos, resiliencia climática, seguridad alimentaria

INTRODUCTION

Developing countries encounter substantial challenges on their path to economic growth. These challenges are particularly attributable to traditional production systems persisting alongside the modern models in developed economies [1], [2]. In this context, adopting new agricultural technologies is a pivotal strategy for enhancing the sector's productivity and sustainability, particularly in tropical regions. These regions play a significant role in meeting the growing global demand for food, even under adverse climatic conditions [3].

In Colombia, the rural sector occupies a key role in political, economic, and social spheres. A significant proportion of the population resides in rural areas, with 32% of the total population living in rural districts. In several departments, including Amazonas, Boyacá, and Cauca, the proportion of the population residing in rural areas exceeds 50% [4]. In this scenario, small producers are crucial in the economy. However, they face significant challenges, such as the inactivity of many producers and the limited size of their agricultural production units (APUs), with an average of only 1.2 hectares for crops and 3.2 hectares for livestock activities [5].

In the Caribbean region of Colombia, APUs play a strategic role in the food safety and livelihood of rural communities. However, these APUs face social conflicts, uncertain property rights, and a lack of innovation. Public policies have historically favored urban development, leaving rural areas at a disadvantage. However, rural capacities and resources are pivotal in addressing poverty and hunger issues. This is in accordance with the Sustainable Development Goals (SDGs) of the 2030 Agenda, which prioritize their eradication [6]. In this regard, [7] state that rural communities are among the most vulnerable to the impacts of climate change due to limited access to adaptive technologies and insufficient institutional support. This highlights the need to integrate rural technological inclusion into climate and development strategies, as unequal access to innovation exacerbates pre-existing social and environmental vulnerabilities.

Globally, the sustainability of the agricultural sector is threatened by water scarcity and soil degradation. Agriculture constitutes almost 70% of the available freshwater use. Salinization affects more than 80 million hectares of irrigated land, reducing soil fertility [8]. In addition, climate change, desertification, and droughts negatively impact agricultural lands, further aggravating the situation [11], [12]. In this context, the implementation of sustainable practices, such as agroecology, emerges as a feasible alternative to confronting these challenges. In this context, implementing sustainable practices, such as agroecology, emerges as a feasible alternative to confronting these challenges by fostering biodiversity and natural processes within agroecosystems, reducing dependence on agrochemical inputs, and mitigating environmental impact [13], [14].

However, the Caribbean region of Colombia remains understudied in terms of research on the effective application of sustainable practices and technologies to the local context. This knowledge gap highlights the lack of studies analyzing the variables that limit the adoption of innovative technologies and practices in APUs. Innovation in the agricultural sector has significantly increased production. However, it has also caused negative impacts, such as biodiversity loss and environmental issues like pollution and the depletion of natural resources. This raises questions about the sustainability of current strategies [15].

This article accurately addresses this lack of information by making a comprehensive diagnosis of the APUs in the Caribbean region, specifically in the departments of Cesar, Magdalena, and Atlántico. The main objective is to identify challenges and opportunities for sustainable management, in addition to proposing strategies to strengthen sustainability, climate resilience, and food safety in the region. To this end, it is necessary to conduct an in-depth diagnosis to identify the problems, demands, and potential of producers to incorporate appropriate technological practices that will help overcome existing obstacles [16].

This approach will contribute to the region's financial and social development, as well as to the preservation of its valuable natural resources, ensuring their availability for future generations.

In this context, global studies have demonstrated the importance of implementing sustainable technologies in agriculture to address the global challenges of food safety, climate change, and poverty reduction. According to the [9],technological innovation in the agricultural sector plays a leading role in eliminating extreme poverty, particularly in developing regions such as South Asia and Africa, where agricultural productivity has stagnated. This approach is equally relevant for Latin America, where incorporating technologies tailored to the local context could significantly increase the resilience of agricultural systems to climate change effects, while improving the livelihoods of rural communities. Similarly, in the regional context, agricultural needs in Latin America and the Caribbean emphasize that agricultural sustainability faces significant challenges requiring the adoption of sustainable and innovative practices. According to the Inter-American Institute for Cooperation on Agriculture [10], the region requires deep transformation of its agrifood systems, driven by sustainable production models tailored to local conditions. This transformation includes the implementation of integrated strategies, such as efficient water and soil management, which have been shown to increase the resilience and productivity of APUs. Thus, the reality of the Colombian Caribbean, characterized by extreme weather changes and resource management limitations, strengthens the need to design technological and sustainable strategies that respond to these regional dynamics.

Recent international experiences have also revealed that the integration of advanced technologies, such as artificial intelligence (AI), in agriculture has proven to be an effective tool for optimizing resources and improving sustainability in complex agricultural systems. An example of this is project Life Triplet in Spain, in which AI tools were applied to efficiently manage fertigation and monitor crop status in real time, thereby achieving a significant productivity increase and an environmental impact reduction [17]. These types of innovations, although developed in different contexts, highlight the potential of smart technologies to address critical challenges in regions with adverse agroclimatic conditions, as is the case of the Colombian Caribbean. The adoption of similar strategies could improve the resilience of APUs in the face of identified resource management constraints.

Given the aforementioned points, agroecology has been identified as a potentially viable strategy. This approach aims to maintain sufficient production levels while reducing reliance on agricultural inputs and agrochemicals, thereby minimizing their adverse effects on human health and the environment [13]. Despite APUs' current limitations, such as small farm size and lack of innovation, these units remain critical to food production and food safety in Colombia. This article endeavors to facilitate the development of effective public policies and the implementation of agricultural development strategies. These strategies have the potential to strengthen the productive capacity of these units and improve producers' quality of life. Moreover, they could promote a sustainable future for both rural communities and the environment.

MATERIALS AND METHODS

The research methodology was meticulously structured across six phases, each with clearly defined objectives. This approach facilitated the collection of pertinent data, thereby ensuring the reliability and validity of the results. The phases were developed sequentially and complementarily: information search, sample calculation, instrument validation, diagnosis, market study, and action plan.

Phase 1: Information Search

In this phase, three fundamental steps were carried out: identification of information sources, data collection, and subsequent analysis.

First, a review of government databases was conducted, including those maintained by the Ministry of Agriculture and Rural Development, along with national open data platforms. These sources provided key information on agricultural production, land use, and weather conditions. In addition, reports from international organizations, such as Food and Agricultural Organization and Intergovernmental Panel on Climate Change, as well as scientific publications from academic databases such as Scopus and Web of Science, were consulted. This review made it possible to gather data on climate challenges, biodiversity, and sustainable practices in agriculture.

The collection of documentary data was complemented with a content analysis, focused on obtaining relevant information on the APUs in the selected departments. The data collected encompassed the crop types, manner in which soil was managed, socioeconomic conditions of producers, and primary environmental challenges they faced. In addition, sustainable technologies and practices that had the potential to enhance the efficiency and sustainability of APUs were incorporated.

Finally, a qualitative and quantitative analysis of the data obtained was performed. Through a descriptive analysis, the relationship between crops, soil characteristics, and local agroecological conditions was evaluated. In addition, the strengths, weaknesses, opportunities, and threats (SWOT) analysis was applied to identify the critical factors impacting the APUs' context.

Phase 2: Sample Calculation

The sample calculation was performed in three stages: identifying the target population, calculating the sample size, and establishing the selection criteria.

The first step was identifying the target population based on the analysis of existing data on the APUs in the municipalities of the departments of Cesar, Magdalena, and Atlántico. Agricultural censuses, Ministry of Agriculture records, and producer associations were consulted to identify the demographic and economic characteristics of rural communities. This information also helped recognize needs and gaps in the data available, guiding the collection of primary data.

The sample size was calculated through a statistical approach adjusted to the research context. This process ensured that the data collected were representative and reliable. The sample selection criteria were established considering factors such as accessibility, representativeness, and diversity of the APUs. Through pilot tests and expert consultation, criteria were adjusted to optimize the sampling strategy.

Phase 3: Instrument Design and Validation

The questionnaire design and validation was conducted in several stages to ensure its quality and relevance.

First, key variables and indicators were identified based on a literature review and expert consultation. The questionnaire included closed-ended and open-ended questions, addressing production, resources, market, technology, and management issues. Likert-type scales were used to measure producer attitudes and perceptions.

The questionnaire was reviewed by a panel of experts to assess its clarity and relevance. The recommendations obtained during this evaluation were added to the final design. Subsequently, a pilot test was conducted with a representative sample of producers, which made it possible to identify comprehension problems and adjust the instrument.

To ensure questionnaire reliability, the Cronbach's Alpha coefficient was used to determine the questions' internal consistency. This analysis allowed adjusting any questions with low consistency, ensuring that the instrument was correctly calibrated before its implementation in the selected municipalities.

Phase 4: Diagnosis

A comprehensive methodology was implemented to carry out the diagnosis of the APUs in the selected municipalities using a previously validated structured survey. This survey made it possible to obtain detailed information on the technical, productive, and financial aspects of the APUs, as well as the sociodemographic characteristics of the unit representatives. It was applied to the prioritized municipalities using a non-probabilistic convenience sampling that guaranteed a representative coverage of the different agricultural regions. The questionnaire, divided into three sections, addressed the following matters:

Identifying APUs: This section collected demographic, location, and land ownership structure data, providing key information on the geographic context and ownership of land used in agricultural activity.

Production activities: An evaluation was conducted of the primary and secondary activities of the APUs, with a focus on analyzing the production destination, adoption trends of agricultural practices, and diversification changes observed in recent years.

Productivity and economic growth: Information was requested on variations in planting area, volume, and value of production in recent years, as well as on key factors for sustainability, such as soil analysis and water source availability.

This diagnosis provided a comprehensive assessment of the performance of the APUs and allowed for the identification of areas of opportunity for the development of improvement strategies.

Phase 5: Market Study

To better understand the context in which the technology will be implemented, a thorough analysis of the market and the existing obstacles to adoption was carried out. To this end, the following activities, among others, were conducted:

Market trend analysis: Current and emerging trends in the agricultural and environmental sectors were assessed, identifying technological innovations, changes in agricultural practices, and consumer trends related to sustainability.

Financial assessment: The financial situation of the agricultural and environmental sectors was analyzed, considering economic stability, access to financing, and investment opportunities.

Regulations review: Laws and regulations affecting technology adoption and trade, including environmental regulations and sustainability policies, were examined.

Moreover, a survey was implemented, and it was applied to a representative sample of producers. The data obtained were analyzed using statistical methods to identify economic, educational, cultural, and logistical barriers. Recommendations were presented to overcome these obstacles and enable technology adoption.

Phase 6: Action Plan

Based on the diagnosis made, an action plan was designed to improve the conditions of the APUs for strengthening their capabilities and overcoming the challenges identified.

Key variables, such as soil management practices, use of inputs, technology applied, and access to resources, were defined. To such end, a questionnaire validated by agricultural experts was designed and applied to a representative sample of producers. Furthermore, surveyors were trained to ensure the quality of the information gathered. An analysis was conducted to identify the internal strengths and weaknesses of the APUs, as well as to assess the external environment. This analysis was undertaken to ascertain the opportunities and threats that could potentially influence the development of the APUs. The results of this analysis were integrated into a preliminary SWOT matrix, which will guide the actions of the improvement plan.

RESULTS AND DISCUSSION

The study results facilitate an analysis of the primary characteristics and challenges of APUs in the Caribbean region.

Characterization of the study area and target population

This section explains the main characteristics of the study area and the special features of the target population to contextualize the socioeconomic, environmental, and productive conditions affecting the development of the APUs.

Department of Atlántico: In the municipalities of Baranoa and Santa Lucía, located in the Colombian Caribbean region, geographical, climatic, and production characteristics were identified that directly influence agricultural development in the area. The village of Pital de Megua, in Baranoa, is located in a region of flat topography, with a warm weather with daytime temperatures above 35°C and nighttime minimum temperatures of around 27°C. This makes agricultural production possible [18]. Relative humidity remains at 49%, with winds blowing predominantly from the south [19].The predominant soil type in Pital de Megua is clay-sandy, which favors the cultivation of crops such as corn, yucca, ahuyama, yams, pigeon peas, zaragoza, millet, and sweet potatoes, among others [18].

Moreover, the municipality of Santa Lucía, which borders the municipality of Campo de la Cruz, Manatí, and the Dique channel, has a tropical climate with temperatures above

30°C year-round and high humidity due to its proximity to the Caribbean Sea [19]. Santa Lucía's soils, predominantly clayey and fertile, favor the production of citrus fruits such as oranges, lemons, and tangerines, as well as vegetables and other short-cycle crops, both for self-consumption and for sale in local markets [18].

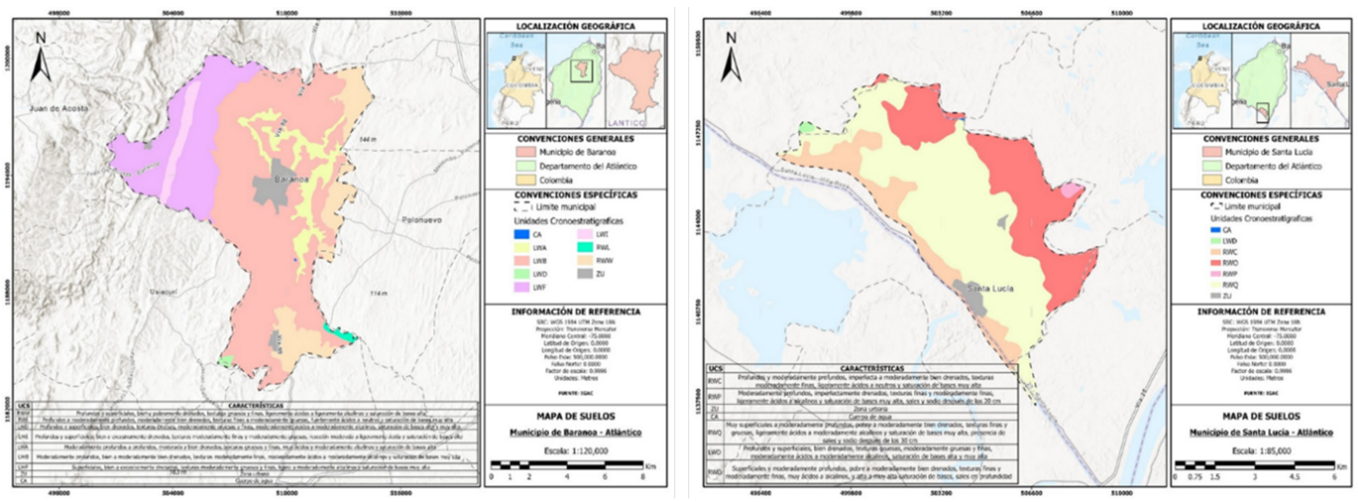

Fig. 1. Map of soil types in the municipalities of Baranoa and Santa Lucía, Department of Atlántico. Source: Authors

In terms of agricultural production, there are approximately 324 APUs in Baranoa, with an average family agricultural unit of 3 hectares. The predominant crops in this area include corn, cassava, ahuyama, and yams, with an average yield of 6 tons per hectare. However, yields can be increased to 40 tons per hectare if more advanced production technologies are adopted [16]. In Santa Lucía, the number of APUs is significantly higher, with about 1,149 units, ranging from small family farms to larger-scale commercial operations. The main crops grown in St. Lucia are citrus, especially oranges and lemons. However, vegetables and other short-cycle products are also grown [16].

Despite the favorable conditions for agricultural production in both regions, there are significant limitations in terms of infrastructure and organization. In Baranoa, the most important crops in 2022 were pumpkin, chili, and eggplant, with a production of 701 tons of pumpkin planted on 46 hectares. In Santa Lucía, 700 tons of guava were produced from 20 hectares of the 38 hectares planted. However, the lack of appropriate infrastructure, such as well-maintained road networks and refrigerated transportation systems, limits the competitiveness of agricultural producers and negatively affects the marketing of products. This entails a significant obstacle to the region's agricultural economic development [20].

It is imperative to acknowledge that, as part of the characterization activities for each study area, an analysis of the agricultural situation was conducted using a SWOT matrix. This analysis enabled the identification of the key aspects influencing the development and sustainability of the region's agricultural activity. Thus, in the department of Atlántico, the strengths identified were fertile lands and a diversity of agricultural products, while the weaknesses included the lack of recent data and infrastructural deficiencies. In terms of opportunities, the importance of developing projects driving agriculture and integrating technology into the sector is highlighted. The threats identified include the negative impacts of climate change and the cost fluctuation of the inputs needed for agriculture.

Department of Cesar: The city of Valledupar, capital of the department of Cesar in Colombia, is located in the northeast of the Caribbean coast, on the banks of the Guatapurí River, in the valley of the Cesar River. This territory, surrounded by the Sierra Nevada de Santa Marta and the Perijá mountain range, has a diverse geography that impacts its climate and economic activities. The city's tropical climate, with an average annual temperature of 28°C, is influenced by two mountain formations, which produce varied environments, from warm heat to permanently snowed areas on the highest peaks during the rainy season [21]. The region experiences two periods of rainfall and two periods of drought, with phenomena such as El Niño and La Niña, which affect agricultural production as the activity depends on the water available for crops [21].

Valledupar is an important center for agricultural, livestock, and agro-industrial production. In terms of agriculture, the department of Cesar stands out for soil diversity ranging from clay to sandy. This is ideal for crops like rice, cotton, and tropical fruits such as avocado, which are key pillars of the local economy. In addition, short-cycle products such as tomatoes, onions, peppers, and yucca are grown, which are essential for food safety in the region [22]. Regarding livestock, extensive systems predominate, mainly Creole cattle crossbred with zebu. Thus, the livestock sector is another economic driver of the municipality.

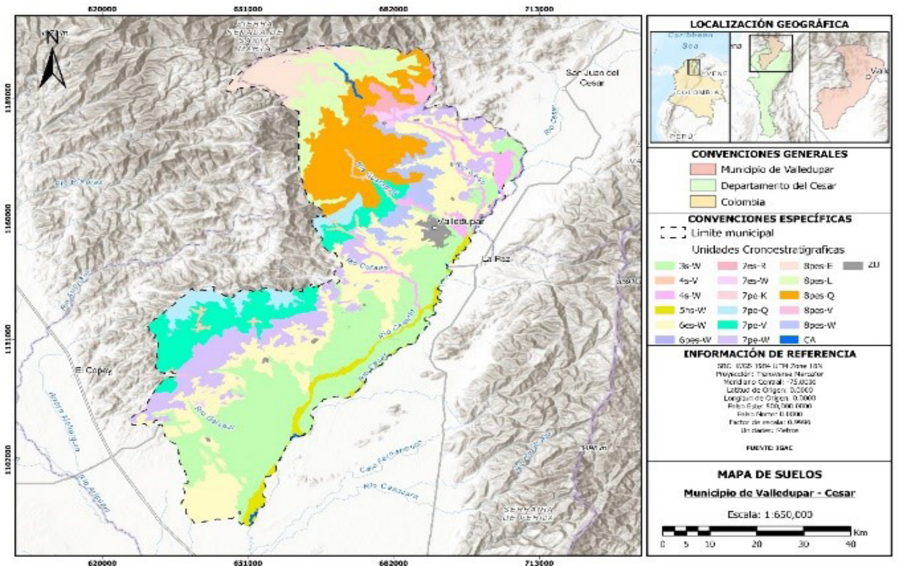

Fig. 2. Map of soil types in the municipalities of Valledupar, Department of Cesar Source: Authors

The agricultural structure in Cesar is varied. As per the National Agricultural Census carried out by DANE in 2014, there are 6,051 APUs in the region, ranging from small family farms to large tracts of land for commercial agriculture. These production units are key for the municipality's economy and employment generation in rural areas [16]. Despite its diversity, the agricultural sector faces challenges, such as a reduction in the area planted and harvested during the period 2011–2016. The area planted dropped from 21,500 hectares in 2012 to 15,533 hectares in 2016, marking a significant reduction [23].

As for agricultural diversification, the department has undergone a remarkable transformation in recent decades. Cotton constituted the primary crop in the 1970s; however, in the present era, oil palm has emerged as the predominant agricultural commodity, with a total area of 75,194 hectares devoted to its cultivation. This is followed by coffee and corn, which collectively encompass 78% of the department's total planted area[23]. In addition, crops such as cassava, rice, and corn continue to be relevant both for food safety and regional and national trade [23].

The marketing of agricultural products in Valledupar is done through different channels, such as local markets, cooperatives, and large distributors. Proximity to urban centers and connection to other regions through transportation networks make the distribution and market expansion of agricultural products possible. In addition, agricultural producers' markets and promotional events allow producers to access new customers and enhance their business opportunities [22].

However, despite its high agricultural potential, the municipality faces significant challenges. The lack of adequate irrigation and drainage infrastructure limits the full development of agriculture. In addition, the effects of climate change, such as increased rainfall variations and temperature fluctuations, may affect production stability. Despite these threats, there are significant opportunities in the sector, especially in the development of technological projects and in the improvement of agricultural infrastructure, which could boost growth and sustainability [21].

Department of Magdalena: The banana area, located in the north of the Department of Magdalena, is a key region for Colombian agriculture, especially in the production of bananas, one of the economic pillars of the region [24]. It borders Ciénaga to the north, Aracataca to the south, Ciénaga to the east, and Pueblo Viejo to the west. Despite its relevance, it faces challenges deriving from agricultural exploitation, which has reduced the capacity to generate stable income for producers.

According to the National Administrative Department of Statistics (DANE), the area is home to about 1,323 APUs, with an average of 5 hectares planted per producer. Banana production predominates, encompassing both small farms and large commercial plantations. The latter, highly mechanized, reflect the central importance of the crop in the region. Other crops, such as bananas and pineapples, also contribute to local agriculture [16].

The climate of the area, influenced by its geographic location, is characterized by temperatures ranging between 24 and 28 ºC (79 and 82ºF). According to the Instituto de Institute for Hydrology, Meteorology, and Environmental Studies (IDEAM), the average annual maximum temperature is 28 °C. The rainy season is distributed over two intense periods: from May to July and from September to November. Rainfall is more moderate in June and August, while the dry season lasts from December to March [25].

The alluvial soils of the region are ideal for tropical crops, especially bananas. The region's agricultural development has been fueled by its high fertility and water retention capacity, which have enabled the production of crops for both the local market and export. In addition, the agricultural infrastructure, which includes irrigation, drainage, and packaging systems, contributes to the efficiency and competitiveness of banana plantations in international markets [24].

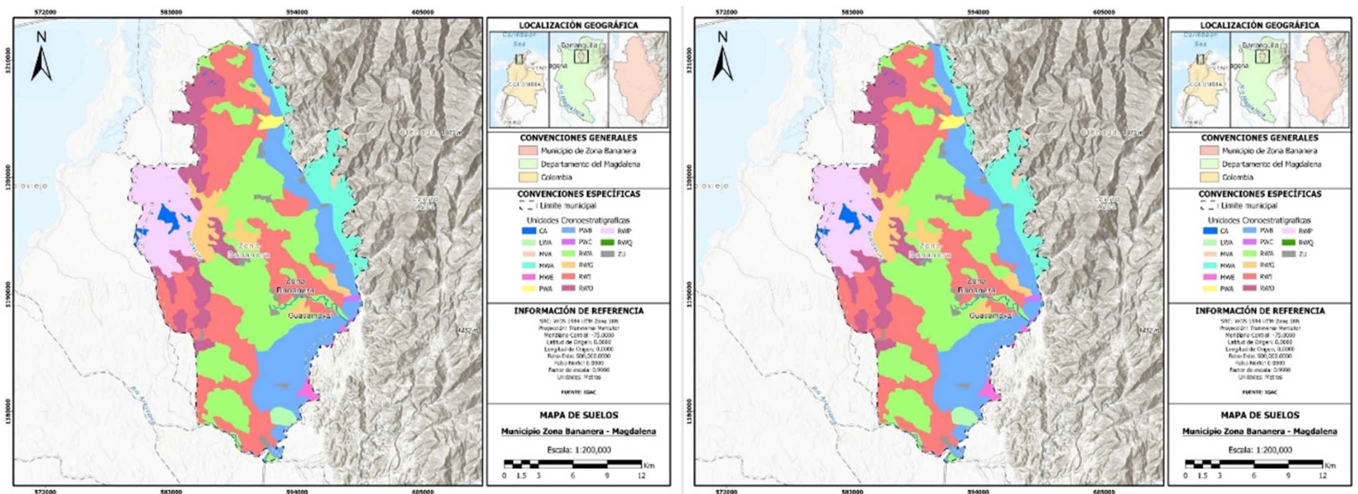

Fig. 3. Map of soil types in the Zona Bananera, Department of Magdalena Source: Authors

Banana cultivation is essential for the local economy, as it generates employment in production, packing, and processing activities. However, dependence on this crop and oil palm (55,000 hectares) limits agricultural diversification. Although crops such as mango are expanding, bananas continue to be the main agricultural product in the area [26].

The strategic location of the Zona Bananera, with access to ports such as Ciénaga and Santa Marta, makes international trade possible, especially with Europe and North America. Road and rail infrastructure also connect the region with the rest of the country, thus favoring logistics development [26].

However, despite its strengths, the region faces significant challenges. Weaknesses include deficiencies in irrigation systems and a high rate of banana bud rot, which can compromise production. The most significant threats are climate change and deforestation, which cause soil erosion and could affect the crop's long-term sustainability [25].

Banana marketing, essential to the area's economy, is highly dependent on exports. Companies seek quality certifications, such as GlobalGAP and Fairtrade, to ensure sustainable agricultural practices and fair labor conditions, which increase their competitiveness in international markets [16]. Despite these efforts, the region continues to face the challenge of fostering cooperation between producers and local authorities to maximize opportunities for economic and social development [26].

Diagnosis of Agricultural Production Units

This section analyzes the current conditions of the APUs in the study area, addressing the main challenges and opportunities identified. This diagnosis enables the identification of the productive dynamics, sustainability limitations, and potential strategies to optimize its functioning in the local context.

Municipality of Baranoa (Atlántico): An awareness-raising workshop on sustainable agrifood innovation systems was held in the town of Pital de Megua, Atlántico, with the participation of agricultural workers. In the process, surveys were administered to 60 producers, representing 60 APUs.

The sociodemographic diagnosis revealed that equal numbers of men and women worked in agricultural activities, highlighting the importance of designing policies addressing the specific needs of both genders. Furthermore, the community exhibited ethnic diversity, comprising Afro-Colombians, mestizos, and indigenous populations. This underscored the necessity for inclusive strategies that acknowledge and respect the cultural distinctiveness of the region. Regarding the level of education, the majority of producers had completed primary education, while a minority had attained higher levels of education. Consequently, the development of training programs tailored to different educational levels was deemed imperative to enhance agricultural skills.

With respect to the duration of operation, the majority of producers had been in business for between one and two years, indicating the recent proliferation of numerous productive initiatives. This underscored the need for ongoing technical support and advice to ensure their consolidation.

Regarding the socioeconomic diagnosis, all the production units operated on areas between one and two hectares for their activities. Leasing was the main form of land ownership (47%), followed by informal situations (35%) and collective ownership (12%). Only 6% of the units were owned individually, involving challenges in terms of stability and long-term planning. In addition, 88% of the producers were mainly engaged in agriculture, while 12% were engaged in livestock activities. This highlighted the importance of diversifying support strategies in both sectors.

Regarding the destination of the production, 43% of the products were for family consumption and 43% were for the private market. Furthermore, 15% of the products were used for animal consumption. The main crops of the region were corn and cassava, each constituting 30% of the total production. Other crops, such as mangoes, pigeon peas, and banana, were also part of the agricultural offer, although in a lesser proportion.

Farming practices included both traditional and modern methods. Accordingly, 56% of the producers used different techniques. A smaller percentage used pesticides (12%), soil burning (10%), or fertilizers (8%). Monoculture was reported by 7%, which evidenced the need to promote more sustainable and diversified practices. However, 60% of the producers had no soil-related education, which limited their ability to optimize resource use and improve productivity. These findings underscored the urgency of implementing programs enabling access to these analyses, thus contributing to a more efficient and sustainable management of APUs.

Municipality of Santa Lucía (Atlántico): In the municipality of Santa Lucía (Atlántico), a workshop on sustainable agrifood innovation systems was held for the staff of local agricultural associations. This event was attended by 72 producers, representing 72 APUs in the community.

In the socio-demographic diagnosis, it was identified that 100% of the production units had between 1 and 2 hectares for their activities. As for gender distribution, equal numbers of men and women were found: 50% of each. This balance reflected an equal involvement in production activities, which is key for implementing inclusive policies in the region.

About ethnicity, 60% of respondents identified as mestizo, 30% as Afro-Colombian, and the remaining 10% belonged to other groups. This diversity highlighted the importance of considering cultural and social traits to promote inclusive and equitable development. With regard to the education levels, 40% of respondents had completed primary school, 30% had completed secondary school, 20% had completed technical or technological studies, and only 10% had access to higher education. These findings proved the need for training programs to strengthen producers' skills.

Regarding experience in their production units, 47% had been working there for more than 16 years, while 24% for between 1 and 3 years, 18% for between 12 and 15 years, and 12% for between 4 and 7 years. These data reflected a balance between consolidated experience and new producers, thus suggesting the need for strategies addressing the support of established producers and the integration of new ones.

In the ancestral knowledge diagnostic, 93% of respondents reported average annual temperatures between 31°C and 41°C, while 7% mentioned ranges between 16 and 30 degrees. In addition, April and October were identified as the months with the highest rainfall (38% each), followed by September (10%) and May (7%). These climatic conditions highlighted the importance of planning appropriate agricultural practices and water resource management strategies.

Regarding the socioeconomic level, 42% of the producers worked on leased land, 26% owned their land, 19% had collective ownership, and 13% had other forms of ownership. Agriculture was the main activity of 82% of respondents, followed by livestock production (10%) and fishing (6%). In addition, 49% of the producers had been engaged in their main economic activity for over 16 years. The rest had shorter careers, thereby showing diversity in experience.

Furthermore, 100% of the producers were organized as individuals, and they had not formed associations or legal entities. This limited their access to financing and technologies. Regarding the destination of production, 57% was sold in the private market and 43% was used for family consumption. The main crops were corn (39%) and cassava (36%), followed by plantain (13%), mango (5%), and banana (1%).

In terms of agricultural practices, 19% used pesticides, 18% used fertilizers, 13% used irrigation systems, and 31% used various methods. However, 97% of producers did not have soil analysis, limiting activity optimization. This underscored the need for programs enabling access to soil studies to enhance agricultural productivity and the region's sustainability.

Zona Bananera (Magdalena): The diagnosis of the APUs in the municipality of Zona Bananera (Magdalena) revealed significant information on the socioeconomic, demographic, and productive characteristics of the agricultural community. During the sensitization, a workshop on sustainable agrifood innovation systems was held, in which representatives from agricultural associations participated. The application of surveys included 109 producers, representing the same number of production units.

In terms of socioeconomic characteristics, all production units had between 1 and 2 hectares for activities. Land ownership was diverse: 50% of the respondents owned their land, 36% operated under a collective ownership system, 10% leased their land, and the remaining 5% had other forms of ownership. In addition, 94% of the producers managed their activities as individuals, 5% operated as legal entities, and 1% did it collectively. These figures revealed that most were individual producers, impacting access to financing, negotiation capacity, and implementation of agricultural practices.

The main economic activity was agriculture, representing 95% of the responses. Fishing and livestock production, although less common, constituted 4% and 1%, respectively, indicating slight diversification. With regard to the destination of production, 52% of the respondents sold to the private market, while 47% used their production for family consumption. This indicated a balance between income generation and food safety. Banana was the main crop, found in 58% of the responses, followed by plantain (11%), cassava (10%), temporary crops (6%), and corn (5%).

In terms of demographics, 50% of the respondents were men and 50% were women, indicating gender parity in agriculture. Furthermore, 58% percent of producers identified themselves as victims of the armed conflict, implying the high vulnerability of the population. As for ethnicity, 11% identified themselves as Afro-Colombian, 2% as persons with disabilities, and 1% as indigenous and mestizos. Regarding the education level, 40% of the producers completed primary school, 30% completed secondary school, 20% did technical or technological studies, and only 10% completed higher education, thus underscoring the need for training programs to improve production skills.

Producers' farming experience varied a lot. Furthermore, 47% had worked in their production unit for more than 16 years, while the rest had shorter careers, indicating a combination of veteran and new producers. These differences in experience suggested the need for support strategies to consolidate knowledge and integrate new producers.

In environmental terms, 89% of respondents reported average annual temperatures between 31°C and 41°C, posing significant challenges for agricultural practices and crop selection. These conditions highlighted the importance of implementing technologies and strategies to optimize production in hot weather. In addition, 60% of producers conducted soil analysis on their farms, while 40% did not. These results underscored the need to boost knowledge on soil physicochemical characteristics to enhance productivity.

With respect to agricultural practices, 20% of farmers utilized fertilizers, 16% employed pesticides, 10% implemented irrigation systems, 8% adapted areas and tools, and 7% engaged in crop planning. Furthermore, 39% reported other practices, a combination of traditional and modern methods of farm management. This diagnosis provided key information for designing strategies to strengthen production units and improve the living conditions of producers in Zona Bananera.

Market Study

Market analysis in the agricultural and environmental sectors revealed a growing trend toward the adoption of innovative technologies aimed at enhancing sustainability and efficiency in the use of natural resources. These trends addressed challenges such as water scarcity and soil degradation, with special interest in solutions such as smart irrigation systems and biotechnologies that increased plant tolerance to droughts and salinity. Interviews with experts and literature review confirmed that these technologies could significantly improve crop resilience, especially in arid regions, as well as optimize resources in controlled environments.

Agricultural practices evolved toward more sustainable and technologically advanced approaches, with a growing interest in precision agriculture. This trend, driven by the need to comply with stricter environmental regulations and increase efficiency, involved the use of sensors and analytical data to optimize decisions related to planting and resource management. In addition, consumers increasingly demanded sustainably grown products, which constituted an opportunity to position technologies that minimized the environmental footprint and fostered responsible practices.

Despite the opportunities, commercializing innovative technologies entailed significant challenges. These included economic obstacles, such as high initial costs and the limited investment capacity of producers, especially in financially constrained regions. Regulatory obstacles were also identified, including slow approval processes and lack of clarity, which hindered the adoption of technologies. To overcome these challenges, it was recommended that communities collaborate with financial entities to develop accessible financing strategies. They should work together with legislators and local communities to design beneficial regulatory frameworks.

As for the financial situation, differences in financial stability in the regions directly influenced technological adoption. Regions with limited access to credit or adequate infrastructure showed a lower willingness to incorporate innovation, while areas with specific financing programs showed higher adoption rates. The need to develop financial products adapted to local conditions to encourage investment in advanced technologies was highlighted.

Finally, sustainability policies promoted the integration of clean technologies in agriculture. Tax incentives and subsidies facilitated the adoption of innovative solutions in certain regions. However, challenges related to local reluctance and regulatory complexity still remained. Accordingly, technology developers must cooperate with legal consultants and participate in public policy forums to anticipate and address regulatory requirements at an early stage, thereby ensuring a favorable environment for technological innovation.

Action Plan

The action plan implemented caused significant results that allowed a comprehensive evaluation of the conditions of the APUs, thus identifying strengths, weaknesses, opportunities, and threats in their environment. This approach made it possible to assess both internal and external factors affecting the sector's sustainability and productivity. The following is a summary of the most relevant aspects of this analysis, providing a basis for planning comprehensive strategies.

Aspect	Description
Strengths	Technical knowledge of some producers in crop management
Weaknesses	Limitations in access to advanced technologies and water resources
Opportunities	Availability of financing for agricultural innovation
Threats	Impact of climate change on agricultural productivity

TABLE 1: SWOT SUMMARY OF THE AGRICULTURAL PRODUCTION UNITS IN THE PRIORITIZED DEPARTMENTS SOURCE: AUTHORS

Based on the information gathered, the SWOT analysis, and the findings, specific strategies were defined to improve agricultural practices, optimize the use of natural resources, and promote APUs' sustainability.

First, information was collected on agricultural practices and the use of natural resources in the APUs of the prioritized municipalities. The surveys applied in rural communities yielded relevant demographic, economic, and productive data. It was found that equal numbers of men and women participated in agricultural activities. There is also significant ethnic diversity, which underscores the need for inclusive and culturally sensitive strategies. However, limitations were found, such as the frequent use of monocultures, limited access to soil analysis, and the predominance of land leasing systems, which affects long-term sustainability. In addition, it was found that production has two destinations: part is for the market, and the other for family consumption. This shows that subsistence and commercial approaches coexist.

The SWOT analysis identified strengths such as natural resources availability, research capabilities, areas suitable for different crops, and traditional agricultural knowledge. Moreover, weaknesses were evidenced, such as the limited dissemination of agricultural programs, lack of market information, and lack of knowledge of added value in production. Opportunities included the growth of markets for organic products, state agricultural promotion programs, and access to virtual information systems. The main threats included competition with imported products, high cost of inputs, adverse climatic factors, and soil degradation.

Based on these findings, the action plan focused on three priority areas:

- Natural resources management: Measures were proposed to preserve soil, optimize water use, and minimize degradation effects. These included the adoption of techniques such as drip irrigation, rainwater harvesting systems, and regular soil testing.
- Introduction of sustainable technologies: The use of digital tools was promoted to access information on market prices, weather conditions, and best agricultural practices, thereby enabling informed decision making.
- Technical capacity building: The training programs were meticulously designed for producers, with a pronounced emphasis on the transfer of contemporary technologies and time-honored traditional knowledge. Additionally, these programs sought to foster the generation of added value within the production chain.

These strategies aimed to address the limitations identified, mitigate risks, and leverage opportunities to enhance APUs' sustainability and productivity, thereby contributing to the agricultural sector's overall development in the region. In this context, the results of the diagnosis revealed specific challenges faced by APUs in each of the departments assessed. These limitations, specifically related to natural resource management and agricultural practices, highlighted the need for targeted interventions to ensure both sustainability and productivity. Below is a summary of the issues identified and the recommendations proposed for each department for the implementation of solutions tailored to local characteristics.

Department	Problem Identified	Recommendation
Atlántico	Soil degradation in 40% of the APUs	Training in soil conservation techniques
Cesar	Deficit in water management in 30% of the APUs	Implementation of efficient irrigation technologies
Magdalena	Soil salinization problems in 70% of the APUs.	Promotion of salinity tolerant crops

TABLE 2: KEY INDICATORS, PROBLEMS, AND RECOMMENDATIONS IN AGRICULTURAL PRODUCTION UNITS BY DEPARTMENT SOURCE: AUTHORS

The findings in the departments of Atlántico, César, and Magdalena highlighted the significant challenges faced by the APUs in relation to sustainability, productivity, and socioeconomic equity. In the case of Atlántico, the high degree of dependence on household consumption in Pital de Megua underscored the significance of these units for ensuring local food safety, as they served as the foundation for food supply in the region. This finding state that agricultural knowledge directly impacts crop quality, soil sustainability, and subsequently food safety. However, the lack of access to soil education and modern technologies, which affected 40% of producers in this area, severely limited the adoption of sustainable technological practices. This problem was confirmed by [16], who highlighted the obstacles to the implementation of innovative technologies in the APUs.

In the department of Cesar, the multidimensional poverty indices, which affected 38% of the rural population, and the degradation of 30% of the soils, were indicative of a structural problem that endangered the sustainability of the agricultural sector. This result aligns with findings by [27] which emphasize that insufficient access to resources and low technology adoption severely impact rural productivity. Furthermore, the limited adoption of modern technologies reflects critical gaps identified by [28] highlighting the need for strategies fostering rural technification to ensure agricultural sustainability.

In Magdalena, problems related to soil salinization and climate vulnerability affected 70% of producers, threatening the viability of key crops such as bananas and oil palm. These findings align with the observations of [3] who argue that adverse climatic conditions and inadequate natural resource management significantly constrain agricultural productivity. However, gender equity in agricultural activities is a positive aspect, aligning with [13] who emphasize social inclusion and gender equality as essential factors for achieving sustainable agricultural production.

Finally, the need to implement agroecological practices and adapted technologies was a shared issue in the three departments analyzed. Agroecology, as indicated by [30] could represent a comprehensive solution to address the problems of sustainability and climate change resilience in rural contexts. This approach, which fosters the use of sustainable and environmentally friendly agricultural practices, coupled with knowledge conveyance and technical training, could have helped close the gaps found in the case studies. Thus, more inclusive and sustainable agricultural development would have been promoted, as suggested by [15] in their research on sustainable agriculture. The findings underscored the significance of designing context-specific public policies and the necessity to cultivate collaboration between local stakeholders, educational institutions, and governments. This collaborative effort was imperative to surmount the prevailing challenges and transition toward a more sustainable agricultural model in the Caribbean region.

CONCLUSION

The study provided a comprehensive diagnosis of the APUs in the departments of Cesar, Magdalena, and Atlántico, identifying the challenges and opportunities faced by the agricultural sector in the Caribbean region. It was found that the APUs play a key role in the local economy, as they are essential for rural employment and food safety. However, it was found that producers faced several limitations, such as resource scarcity, climate change, and the volatility of agricultural prices. These hindered producers' ability to increase yields and ensure the sustainability of their activities.

In this context, the importance of agroecology and the adoption of innovative technologies to enhance APUs' productivity and sustainability was highlighted. Despite the prevailing economic challenges, agricultural producers had devised and implemented adaptation strategies, including agroecological production methods, the exchange of agricultural goods, and the establishment of solidarity networks. These strategies revealed the potential of small producers to strengthen their production units through creative solutions. However, greater institutional support was required to optimize these efforts.

The comparative analysis between the departments revealed that APUs faced different levels of vulnerability, but they all shared the need to improve agricultural infrastructure, mainly in terms of water and soil management. It was identified that the implementation of efficient irrigation systems and the use of digital monitoring technologies could have significantly improved productivity, allowing for a more efficient management of natural resources.

In examining the impediments to the integration of novel technologies, it was ascertained that financial constraints and a paucity of technical expertise constituted significant barriers. To overcome these challenges, it was essential to implement training and technical support programs, thereby increasing the propensity of producers to adopt innovative technologies. The creation of financing strategies and subsidies was also presented as a key measure to enable access to technologies for increasing the APUs' resilience in the face of climatic challenges.

The study also underscored the importance of strengthening producers' organizational skills, promoting the formalization of their production units and the establishment of associations to improve their access to financing and markets. In addition, it was recommended that a monitoring and evaluation system be implemented to track the progress of the strengthening strategies, ensuring that the interventions are effective and sustainable in the long term.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

E. Olivero-Vega: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft. A. Torregrosa-Espinosa: Formal Analysis, Software, Visualization, Validation, Writing – Review & Editing. M. Iglesias-Navas: Resources, Supervision, Validation, Writing – Review & Editing. A. Quintero-Linero: Investigation, Validation, Data Curation. D. Blanco-Alvarez: Conceptualization, Methodology, Project Administration, Supervision, Funding Acquisition, Writing – Review & Editing.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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